QUANTITATIVE *IN-SITU* NANOINDENTATION OF THIN FILMS IN A TRANSMISSION ELECTRON MICROSCOPE

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A unique *in situ* nanoindentation stage has been built and developed at the National Center for Electron Microscopy in Berkeley, CA.[1,2] By using piezoceramic actuators to finely position a 3-sided, boron-doped diamond indenter, we are able to image in real time the nanoindentation-induced deformation of thin films. Recent work has included the force-calibration of the indenter, using silicon cantilevers to establish a relationship between the voltage applied to the piezo-actuators, the displacement of the diamond tip, and the force generated.

In this work, we present real time, *in situ* TEM observations of the plastic deformation of Al thin films grown on top of lithographically-prepared silicon substrates. The *in situ* nanoindentations require a unique sample geometry (see Figure 1) in which the indenter approaches the specimen normal to the electron beam. In order to meet this requirement, special wedge-shaped silicon samples were designed and microfabricated so that the tip of the wedge is sharp enough to be electron transparent.

Figure 2 shows the results from the force-calibration of the nanoindenter. Piezoceramic actuators, while ideal for nano-scaled positioning, are far from ideal for force generation. This results from the fact that force generation from piezo-actuators is load-displacement coupled. As the graph in Figure 1 shows, for a given applied voltage, both a large force with a small displacement, or a large displacement with a small force are possible. By carefully calibrating the nanoindenter with two different silicon cantilevers in the TEM, we have been able to decouple the load and displacement so that we can quantitatively describe the force applied during an *in situ* nanoindentation.

Figure 3 shows images taken from a video of an *in situ* nanoindentation of Al in dark field. The dislocations moving along the {111} planes as a result of the indentation are clearly evident. The nanoindentation of Al thin films will be discussed with relevance to nanoindentation phenomena such as "pop-in" behavior, dislocation nucleation, and the interaction of dislocations with the substrate and grain boundaries.

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[1] Wall, M. and U. Dahmen, *Microscopy and Microanalysis,* **3**, 1997
[2] Stach, et al. , *Microscopy and Microanalysis,* submitted